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MATERIALS FOR SPACE FLIGHT

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MATERIALS FOR SPACE FLIGHT

This lecture discusses the spectrum of thermal environments and functional requirements for materials used in space vehicles. Two major criteria emerge: a) a desire by designers to operate materials at the highest permissible temperature and b) the necessity to minimize the structural weight. Future possibilities in materials are investigated in these categories: For maximum temperatures the metals, carbon and carbides are studied, while for minimum weight requirements fibered materials — for tension elements — and beryllium, — for buckling components — are discussed. (See schematic Fig. 1.) Improvements in performance of space flight vehicles are listed, as afforded by the advanced materials studied. Topics for research in each material area are offered.

INTRODUCTION

The age of space flight will demand huge advances in all technological fields, and the technology of construction materials for space vehicles will have to undergo just as vast improvements as all the other fields.

It is tempting to think in fairly conventional terms of the building materials of which vehicles will be composed, since quite passable vehicles with limited capabilities could be designed today, using present-day materials, as in the Explorer. But if we deliberately look beyond today's materials, as we will try in this presentation, and if we speculate uninhibitedly in future possibilities, a host of significant improvements may be uncovered. Indeed, our speculation, a touchy business at best, did reveal that many superior materials could be developed with a little imagination and a lot of willingness to take risks in materials research.

Some generalizations emerge from the multitude of requirements that determine the choice of materials for a vehicle. The thermal environment

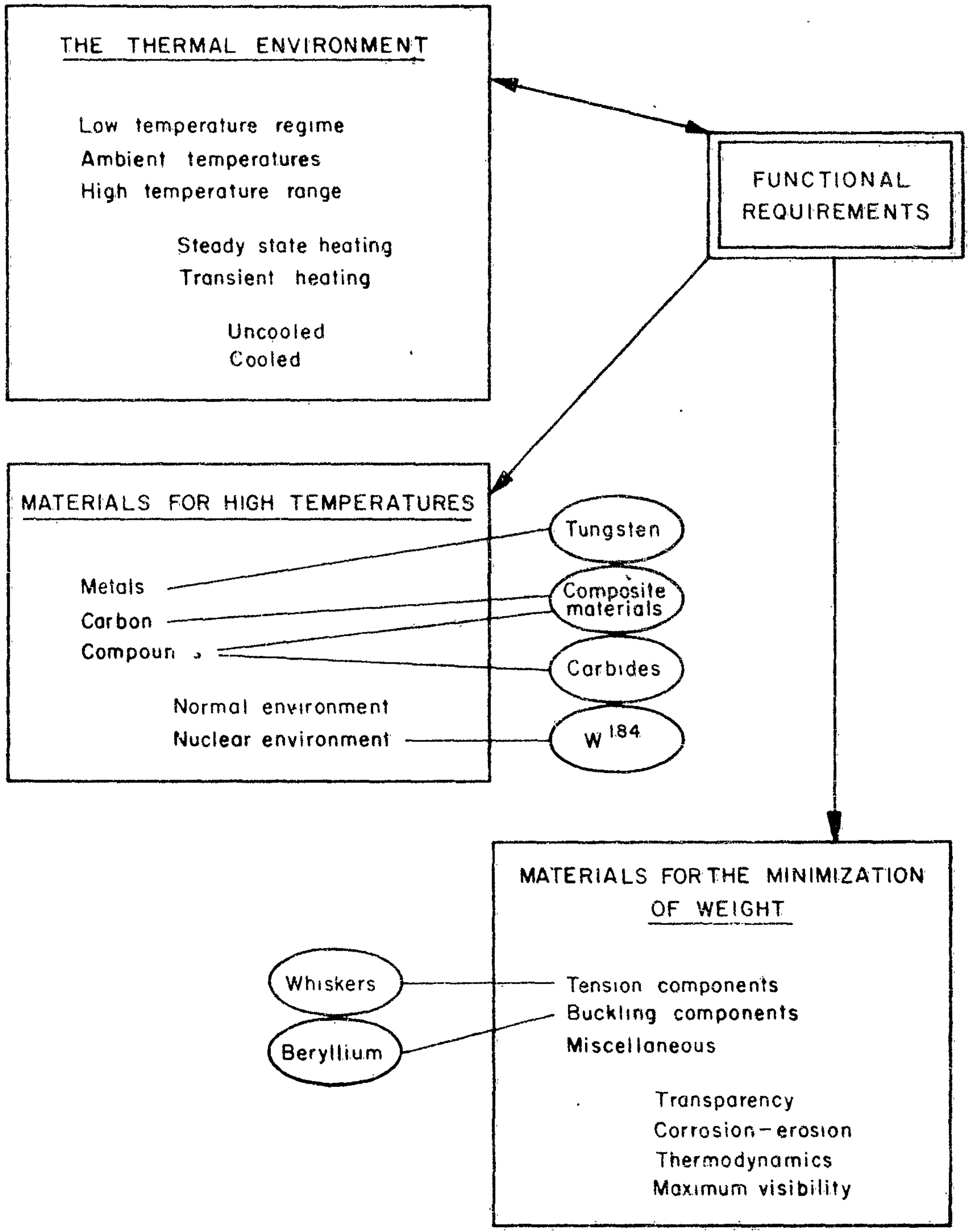

Fig. 1 —— Environments, requirements and some future possibilities for construction materials

of the material is of primary consideration: temperature regimes, temperature histories and temperature gradients influence most radically the selection of materials. In the low-temperature regime (as for example for liquid hydrogen tanks) fewer unsolved problems exist than in the high temperature range experienced by the propulsion unit and in the reentry section. In the ambient temperature region, say between -100°F and 200°F, the materials experience amassed so far permits reliable designs of such structures as the cabin, some of the tanks and most of the equipment and controls.

Furthermore, within each regime, materials choice is affected by the time of exposure. Steady-state (constant) heating, as in the powerplant, is handled by very different materials than transient (rapidly changing) heating, as it may occur in the reentry structure. Finally, the temperature gradient within a material becomes an important factor, when the steadily heated structure is cooled by some fluid.

Once the thermal environment can be defined, the other design criteria — the functional requirements — tend to fall into two broad categories: materials permitting the maximization of operating temperatures, and materials permitting the minimization of weight. These two classes of construction materials will be the field for our following remarks, though overlapping and of a simultaneous nature.

MATERIALS FOR HIGH TEMPERATURE

Metals, because of their strength and ductility, have been the preferred materials of vehicle construction in the past. Their various degrees of ductility permitted freedom of design, a certain inherent margin of safety and ease of fabrication. For contrast, metallic compounds — such as metal

carbides, oxides, nitrides, etc. — have mainly superior strength at higher temperatures accompanied by a lack of ductility. In this section metals and compounds will be separately discussed, as well as carbon, a most interesting material with valuable properties intermediate between those of metals and compounds.

Metals

The strength of a polycrystalline metal deteriorates most rapidly around its recrystallisation temperature. Furthermore this recrystallization temperature (or softening temperature) is linearly related to the melting point as shown in Fig. 2 (Ref. 1). Intensive metallurgical development and the appropriate alloying of a metallic element can usually accomplish a rise in softening temperature with a slight lowering of the melting point as shown in the shaded area in Fig. 2. In a few instances polycrystalline metals have been used at temperatures even higher than the softening temperature, within a few hundred degrees of their melting point, in the unstressed state.

The best prospect for a massive metal for the highest temperature is tungsten (chemical symbol, W); it could be developed to withstand stresses at continuous exposure to $3000^{\circ}F$ and, in certain forms, much higher. There is some modest metallurgical work being done in tungsten alloying or additives, but little effort exists toward the alleviation of such problems with tungsten as oxidation resistance, or acquisition of the unusually high-power equipment required for tungsten research.

Nature benignly bestowed upon us a low cross-section isotope of tungsten, W^{184}, in case we wish to use this metal where neutron absorption is not desired. For additional good measure this isotope, (neutron absorption cross-section: 2 barns) is also the most plentiful of the multitude of tungsten

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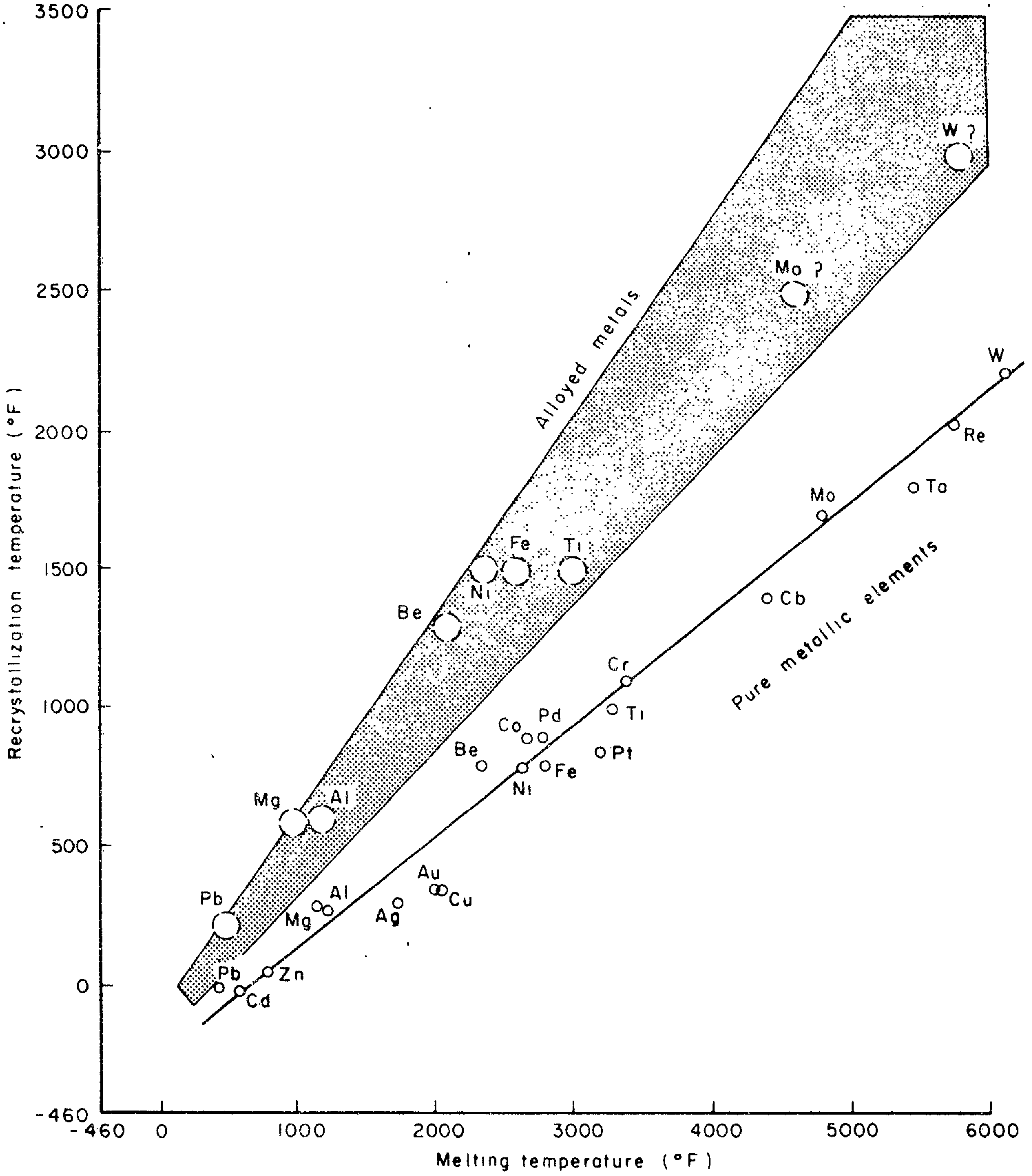

Fig. 2 —— The relation between the recrystallization temperature and the melting temperature of metals

isotopes, comprising 30 per cent of its natural occurrence.

Carbon

Books could be written about the anomalies of carbon (Ref. 2). It will suffice to say that its basic nature is that of a non-metal, still displaying a tantalizingly small degree of ductility. Its very low density (0.06 lb/in^3 against tungsten's 0.7 lb/in^3), cannot be related to its high melting point (6700°F against tungsten's 6170°F). Just to be different, its strength and modulus increase with temperature up to its recrystallization temperature of 4500°F (see Fig. 3); and, in this vein of cooperativeness, it displays a very low neutron absorption cross section.

A high specific heat combined with a high heat conductivity, in addition to the above properties, makes carbon an attractive material for transient heating conditions — as a heat sink. A recent study by the NACA concluded that a reentry nose cone of carbon should weigh slightly less than one made of beryllium, and both the beryllium and carbon cones would weigh one-sixth as much as one made of copper, the next nearest competitive material.

But let us not overlook the fact that possible structural uses of carbon are severely restricted by its present-day low ductility, and unless this ductility can be raised considerably, it will be very difficult to put carbon to any extensive or massive application. A possible solution to this problem may be the development of composite materials: combinations of filaments or films surrounded by a ductile matrix probably metallic. Such an arrangement might retain most of the favorable strength-at-temperature characteristics of carbon and significantly improve its available ductility.

Another noteworthy possibility with carbon has been the growth of fine filamentary crystals (commonly called "whiskers") and of thin films of carbon,

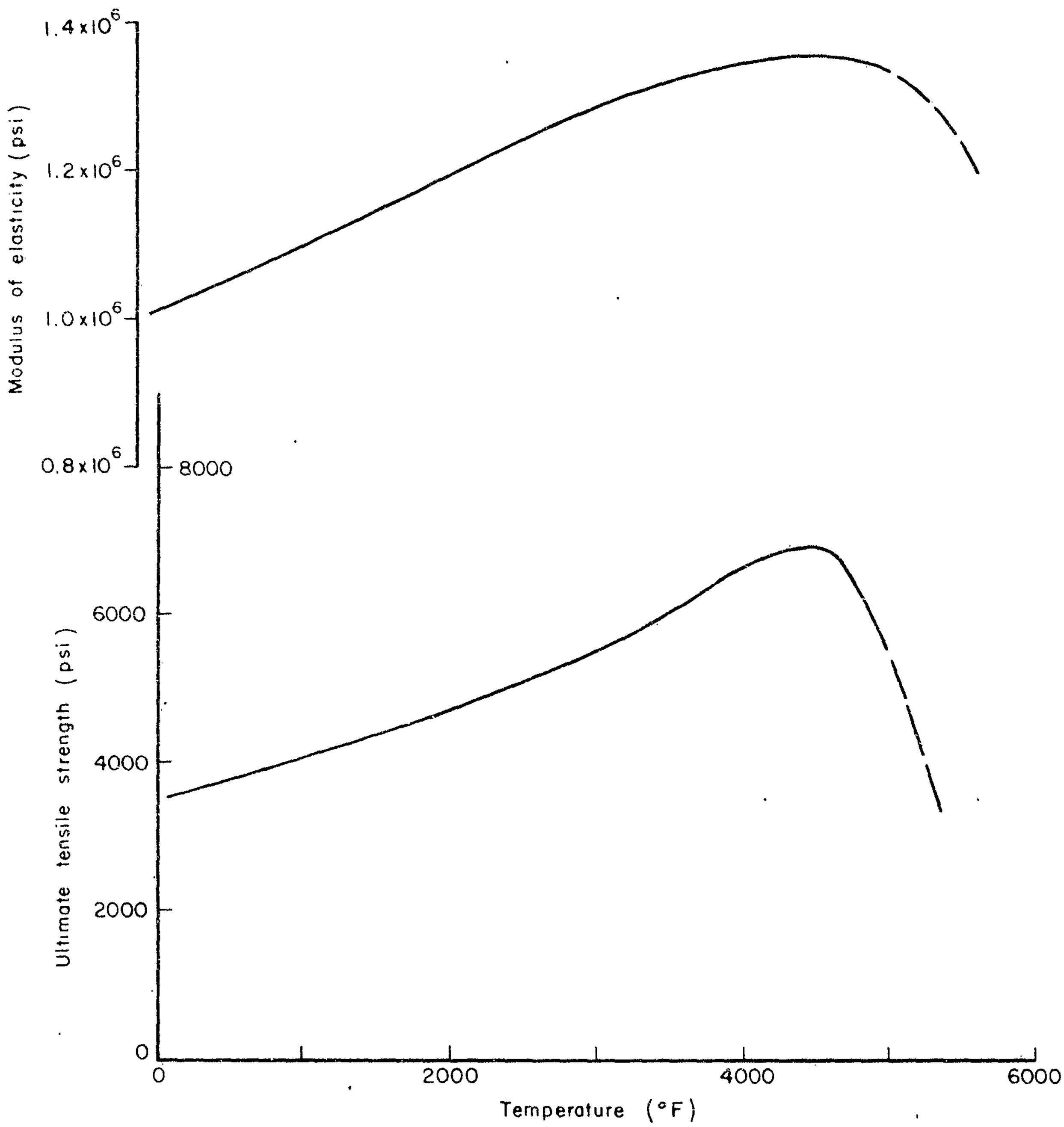

Fig. 3 — Strength and modulus of carbon versus temperature

exhibiting tensile strengths several times higher than those of bulk graphite. These "whiskers" may hold the key to a vast enhancement in the strength of graphite.

A disadvantage of carbon is the way in which it reacts with oxygen and hydrogen. But success in solving these problems seems possible with surface coatings or impregnation, in which case carbon would find notable applications when exposed to high temperature gas flows, as in the leading portions of a reentering body or in a rocket nozzle or vane.

Compounds

Carbides of metals tend to have higher melting points than the oxides, borides, or nitrides (Table 1). Hafnium and tantalum carbides have the highest melting point of any known substance, above 7000°F, but also have such undesirable properties as high density and large neutron absorption cross section. On the other hand zirconium carbide and columbium carbide have half the density and one-hundredth of the absorption cross section of HfC and TaC, but also have a lower melting point, around 6400°F.

Ceramics, such as the carbides and oxides, do not exhibit any plastic deformation when stressed at the rates encountered in structural practice. After meticulous surface preparation, and at extremely low stress rates, Professor Earl R. Parker of the University of California has induced plastic flow in magnesia (MgO), but only in fresh-cut crystals and only in one orientation. However faint this glimmer of hope for developing "ductile ceramics," it still remains an attractive field of investigation, since brittleness is the only major, and so far unsurmountable, obstacle to the widespread use of ceramics as structural components in powerplants.

The technique of prestressed ceramics (Ref. 3) is being investigated as a means of circumventing the brittleness problem: it is a procedure that

Table 1. PROPERTIES OF COMPOUNDS

Material	Formula	Density (lb/in^3)	Thermal Neutron Absorption Cross Section (Barns)	Melting Point ($^{\circ}F$)
CARBON	C	0.07	0.0045	6650
CARBIDES:				
Hafnium	HfC	0.441	115	7030
Tantalum	TaC	0.523	21.3	7010
Zirconium	ZrC	0.242	0.185	6390
Columbium	CbC	0.283	1.1	6330
Titanium	TiC	0.154	5.6	5680
Tungsten	WC	0.560	19.2	5190
Vanadium	VC	0.194	4.7	5130
Aluminum	Al_4C_3	0.108	0.874	5070
Molybdenum	Mo_2C	0.307	4.8	4880
Thorium	ThC_2	0.347	7.0	4810
Boron	B_4C	0.091	3000	4400
Uranium	UC_2	0.408	7.43	4300
Calcium	CaC_2	0.074	0.439	4170
Silicon	SiC	0.116	0.135	3990
Beryllium	Be_2C	0.088	0.0225	3900
Chromium	Cr_3C_2	0.241	8.7	3400
OXIDES:				
Thorium	ThO_2	0.372	7.0	5520
Hafnium	HfO_2	0.350	115	5090
Magnesium	MgO	0.120	0.059	5070
Zirconium	ZrO_2	0.193	0.193	4710
Cerium	CeO_2	0.260	0.70	4710
Calcium	CaO	0.122	0.43	4680
Beryllium	BeO	0.103	0.0092	4590
Gadolinium	Gd_2O_3	0.267	88000	4260
Uranium	UO_2	0.394	7.42	3950
Titanium	Ti_2O_3	0.166	11.2	3870
Aluminum	Al_2O_3	0.137	0.43	3660
Titanium	TiO_2	0.150	5.6	3330
Silicon	SiO_2	0.084	0.13	3110
BORIDES:				
Zirconium	ZrB_2	0.220	1500	5430
Tantalum	TaB_2	0.447	1500	5430
Tungsten	WB_2	0.461	1500	5250
Columbium	CbB_2	0.252	1500	5250
Titanium	TiB_2	0.162	1500	4710
Uranium	UB_2	0.459	1500	4290
Calcium	CaB_6	0.089	4500	4060
Lanthanum	LaB_6	0.094	4500	4010
NITRIDES:				
Tantalum	TaN	0.589	23	5590
Boron	BN	0.079	750	5430
Zirconium	ZrN	0.256	1.97	5400
Titanium	TiN	0.196	7.38	5340
Columbium	CbN	0.303	2.88	4660
Vanadium	VN	0.221	6.48	3720
Silicon	Si_3N_4	0.124	7.51	3450

exploits the invariably high compressive strength of most ceramics. The material would be permanently compressed by means of highly stretched metallic wires, and the structure built up of such prestressed materials would be so proportioned that tensile stresses from loads would never exceed the locked-in compression, thus insuring at all times that the material is in compression. The analogous technique of prestressed concrete has been very successful in civil engineering structures.

Another alternative is the technique of composite materials, that suggests itself again regarding this brittleness problem. Brittle glass, in brittle glass fiber form, makes up a reasonably ductile composite when impregnated in plastics: analogously fibers of carbides imbedded in a matrix of some refractory metal might result in a usable material.

It is interesting to see what the temperature limitation might be for such materials ceramics, if the problem of brittleness could be solved in some manner. The relation between melting point and softening temperature for the carbides (Fig. 4) is sufficiently reliable to indicate some upper limit around 5000°F – not much beyond carbon's potentiality.

Even if these future ceramics were to be much stronger than carbon, we should not forget that they are also far denser, so that in a structural comparison with carbon there emerge no distinct advantages to the use of ceramics. For example, the theoretical $\frac{\text{density}}{\text{strength}}$ ratios of carbon and the best carbides differ by very little at 4500°F, probably not enough to warrant an intensive effort in carbide research, especially if it were at the expense of research in carbon.

THE MINIMIZATION OF STRUCTURAL WEIGHT

The urgency for minimizing the weight of flight vehicles has been proportional with the difficulty of the task imposed upon these vehicles.

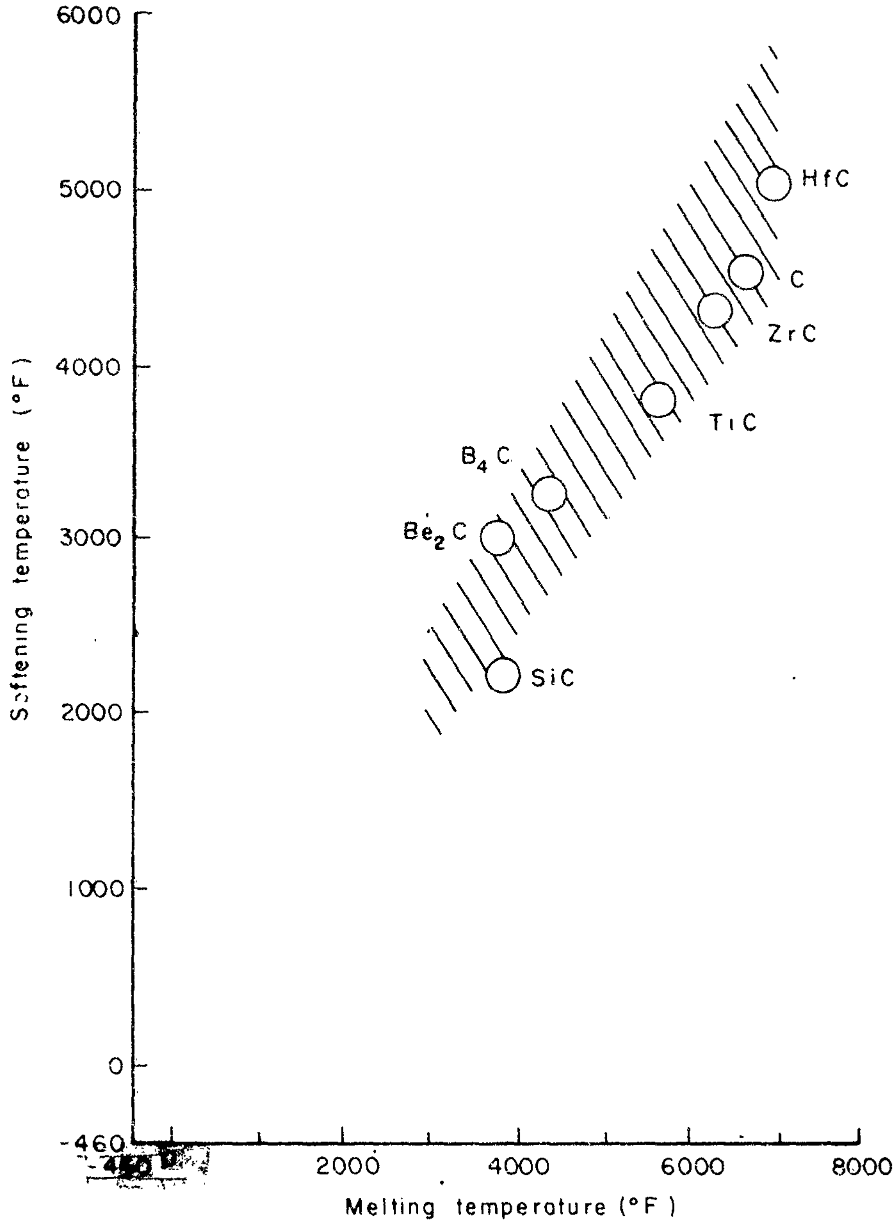

Fig. 4 — Softening versus melting point temperatures for carbon and carbides

By now, it is a platitude in astronautical circles to talk of reducing to an irreducible minimum the weight of such items as the tanks, cabins, powerplants, equipment, controls, coolants, etc. With such a pressing demand, a demand that has been with us now for decades of flight, one would believe at first that most possibilities for radical improvement in structural materials for minimum weight design have been exhausted. This section will attempt to show that such is not the case; on the contrary, there still lie ahead of us good potentialities, as yet untapped, for greatly reducing weight down to fractions of present designs.

The section will be arranged along the two major classifications of loading conditions encountered in astronautical vehicles, namely components designed by tension criteria and components designed by compression buckling criteria. A third category will also be mentioned, namely components designed primarily by other criteria than loads. The proportions of structural weight of space vehicles in each of these categories is probably such that the predominant portion of structural weight will be designed by tension criteria, and the small remainder is divided between components designed by buckling and by other non-load criteria.

Tension Components

The ultimate goal in the improvement of structural materials has been the achievement of the tensile strength available from atomic cohesion. To this day the highest strengths developed by metallurgical means is still a small fraction of the strength theoretically obtainable from the flawless cohesion of atoms in a metal. But the goal of materials as strong as the bond between atoms is not an idle dream: today, in a few laboratory experiments, fine crystal fi aments — "whiskers" — have been grown, demonstrating

phenomenal strengths, in some instances approaching the theoretical limit of atomic cohesion (Ref. 4).

It is fruitful to speculate on how to utilize "whiskers" for structural purposes: we believe that the idea should be entertained, with interesting possibilities all the way from the production, analysis and economics, to spelling out a "whisker" research program (Ref. 5).

Production. First, no unsolvable problems presented themselves for growing substantial quantities of whiskers, and for lining them up and harvesting them. Next, these whiskers could presumably be woven into cables or sheets just as with textile fibers or with fiberglass. Finally we envisage at least two possibilities for binding together these whiskers, namely plastic matrix impregnation (as with fiberglass) or by pressing and sintering as in powder metallurgy.

Having postulated some hypothetical production means, it is revealing to try predicting the properties of whisker structural materials.

Properties of whiskers and of materials made from whiskers. The high strength of whiskers is due to the phenomenon of strength increase in a crystal as its dimensions decrease. It is only in the last few years that this strengthening was demonstrated to continue at a steeper rate as crystal sizes are reduced, say, beyond one-ten thousandth of an inch (Fig. 5). The ultimate goal of finding whisker strength near the atomic cohesion level was achieved only in the past two years.

This tremendous strengthening effect is quite general in materials, applying to whiskers of metals, carbon, oxides, carbides, etc. Theoretical explanations have been made for the strengthening phenomenon , and it now appears that it is due to the unusually low incidence of dislocations and high surface tension forces that must probably occur within the limited

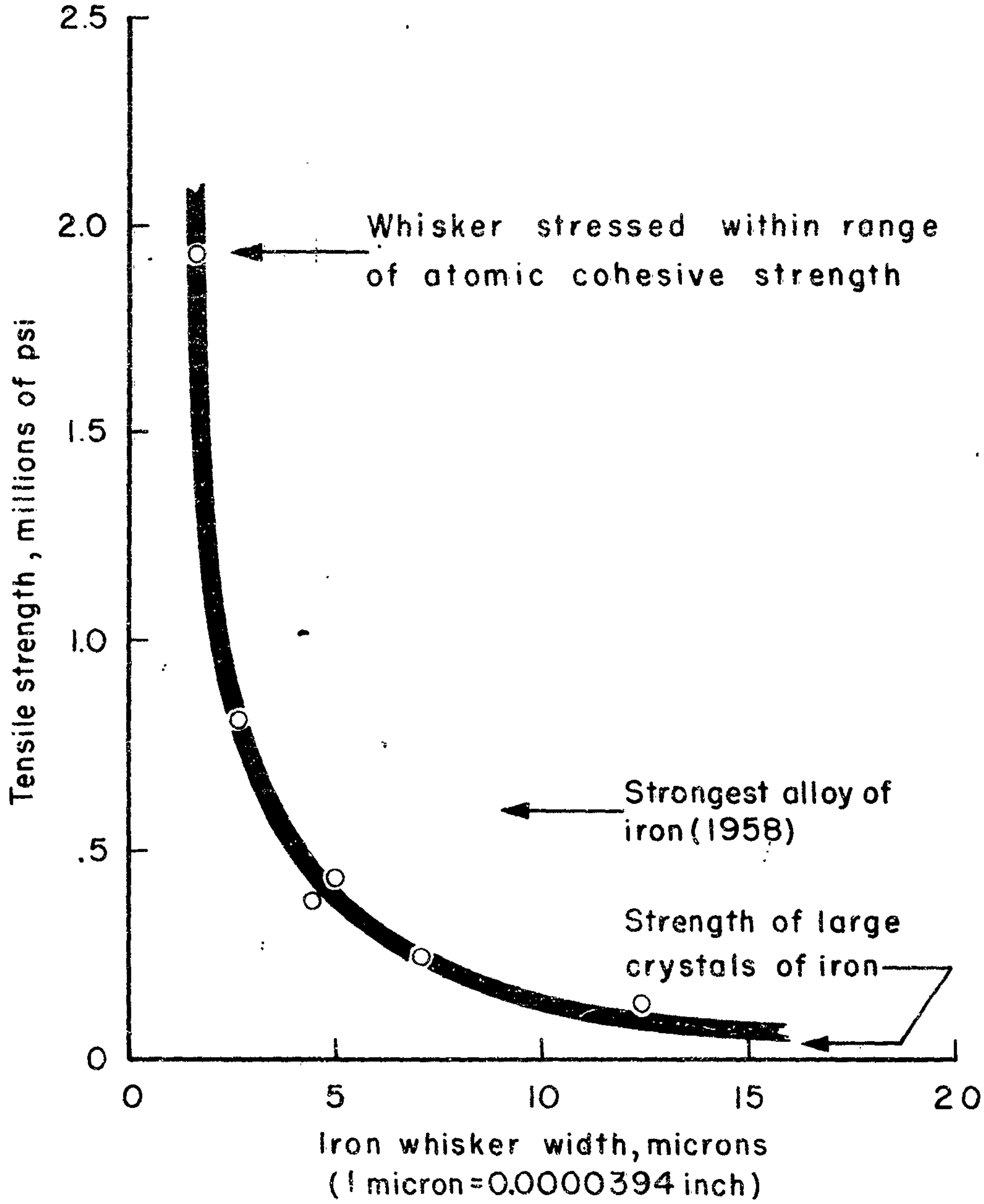

Fig. 5 – The strength of pure iron whiskers as a function of their width

small width of the whiskers. Theories are also available predicting what strength of atomic cohesion would result from a perfect crystal lattice – that is the strength limit of an ideally "perfect" material as approximated by the situation in whiskers: the ultimate tensile stress should be between one-tenth and one-fortieth of the modulus of elasticity.

The reported best strengths of whiskers (Table 2) show that indeed the ultimate stress is of the order that theory predicts for a "perfect" material.

Table 2

TENSILE STRENGTH OF THE STRONGEST WHISKERS

Material	Modulus of elasticity, psi	Ultimate tensile stress, psi	$\frac{\text{stress}}{\text{modulus}}$ ratio
Silicon	23,000,000	550,000	$\frac{1}{42}$
Carbon	1,000,000	88,000	$\frac{1}{11}$
Iron	29,000,000	1,900,000	$\frac{1}{15}$
Silver	11,000,000	240,000	$\frac{1}{46}$
Copper	18,000,000	430,000	$\frac{1}{42}$
Quartz	11,000,000	600,000	$\frac{1}{18}$
Zinc	15,000,000	320,000	$\frac{1}{47}$
Cadmium	10,000,000	130,000	$\frac{1}{77}$
Sapphire	74,000,000	1,700,000	$\frac{1}{43}$

It is customary to use the ratio $\frac{\text{density}}{\text{ultimate tensile strength}}$ when comparing weights of tension structures made of various materials. Now, since the ultimate strength of the best whiskers is some fraction of their modulus, the criterion for choosing among the multitude of possible whisker materials is the minimization of their $\frac{\text{density}}{\text{modulus}}$ ratio. This ratio, listed among other data in Table 3, and combined with the previously noted data on softening

Table 3
SOME MECHANICAL PROPERTIES OF MATERIALS

Atomic Number	Symbol	Element	Density (lb/in^3)	Modulus of Elasticity (millions of psi) at 70° F	Density / Modulus ($\frac{1}{in} \times 10^9$)	Melting Point (°F)
3	Li	Lithium	.019	2	9.5	370
4	Be	Beryllium	.066	44	1.50	2340
5	B	Boron	.083	50	1.66	4200
6	C	Carbon	.060	1-2	30	6700
12	Mg	Magnesium	.066	6.5	10.2	1200
13	Al	Aluminum	.100	10.6	9.4	1200
14	Si	Silicon	.084	23	3.6	2600
20	Ca	Calcium	.056	3.5	16	1560
22	Ti	Titanium	.170	16.7	10.2	3300
23	V	Vanadium	.217	24	9.0	3150
24	Cr	Chromium	.260	45	5.8	3400
25	Mn	Manganese	.268	23	11	2300
26	Fe	Iron	.283	29	9.8	2800
27	Co	Cobalt	.327	32	10.2	2700
28	Ni	Nickel	.322	31	10.4	2650
29	Cu	Copper	.324	18.5	17.5	2000
30	Zn	Zinc	.258	15	17.2	790
32	Ge	Germanium	.194	12	16	1750
33	As	Arsenic	.207	11	19	1500
38	Sr	Strontium	.094	2.5	38	1540
40	Zr	Zirconium	.231	12	19.2	3200
41	Cb	Columbium	.310	23	13.5	4400
42	Mo	Molybdenum	.369	52	7.10	4800
43	Tc	Technetium	.415	59	7.0	4200
44	Ru	Ruthenium	.450	63	7.1	3500
45	Rh	Rhodium	.450	55	8.2	3600
46	Pd	Palladium	.434	17	25	2800
47	Ag	Silver	.379	11.2	34	1760
48	Cd	Cadmium	.313	10	31	600
50	Sn	Tin	.264	7.8	34	450
51	Sb	Antimony	.239	11.3	21	1200
52	Te	Tellurium	.225	6	37	850
56	Ba	Barium	.130	2	65	1300
57	La	Lanthanum	.222	7	32	1250
58	Ce	Cerium	.253	5	51	1100
72	Hf	Hafnium	.411	12.1	34	3200
73	Ta	Tantalum	.601	27	22.3	5450
74	W	Tungsten	.697	52	13.4	6170
75	Re	Rhenium	.743	66	11.3	5760
76	Os	Osmium	.813	83	9.8	5000
77	Ir	Iridium	.815	78	10.4	4450
78	Pt	Platinum	.775	24	32	3200
79	Au	Gold	.698	12	58	2000
82	Pb	Lead	.410	3.8	108	620
83	Bi	Bismuth	.354	4.6	77	500
90	Th	Thorium	.422	22	19	3250
92	U	Uranium	.676	30	22.5	2060

Material	Chemical Symbol	Density (lb/in^3)	Modulus of Elasticity (millions of psi) at 70° F	Density / Modulus ($\frac{1}{in.} \times 10^9$)	Melting or Decomposition Point (°F)
Beryllium Carbide	Be_2C	.088	45	1.95	3800
Beryllium Oxide	BeO	.103	55	1.87	4580
Boron Carbide	B_4C	.091	65	1.40	4500
Magnesium Oxide	MgO	.129	12	10.8	5070
Aluminum Oxide	α-Al_2O_3	.137	52-74	2.6	3660
Silicon Carbide	SiC	.115	70	1.6	4350
Silicon Oxide	SiO_2	.083	11	7.5	3150
Titanium Carbide	TiC	.178	51	3.5	5700
Titanium Oxide	TiO_2	.170	14	12.1	3330
Vanadium Carbide	VC	.210	39	5.4	5130
Zirconium Carbide	ZrC	.242	49	4.9	6400
Zirconium Oxide	ZrO_2	.193	36	5.4	4700
Zirconium Silicate	$ZrSiO_4$	.154	24	6.4	4600
Molybdenum Carbide	Mo_2C	.320	33	9.7	4870
Tantalum Carbide	TaC	.523	42	12.5	7020
Tungsten Carbide	WC	.567	102.5	5.5	5030
Thorium Oxide	ThO_2	.346	21	16.5	5900

temperatures (Figs. 2 and 4) yielded a comparison among all the possible materials and temperatures. This comparison, shown graphically in Fig. 6, shows the hypothetical relative weight of equal-strength whiskers of various materials at various temperatures, for the least-weight (most efficient) materials, using a beryllium whisker as a unit-weight standard, since it happens to be the lightest of all, at ambient temperature.

Knowing which are the most desirable materials (the ones shown in Fig. 6), it is possible to calculate the structural properties of hypothetical whisker materials. These properties have been listed in Table 4, as calculated for 70°F on the basis of beryllium whiskers and some reasonable assumptions as to matrix-whisker compositions, strain limitations and future production techniques.

Table 4

STRUCTURAL PROPERTIES OF WHISKER MATERIALS

Property	Whisker Material made into Cables	Sheets	Conventional metal Titanium
Density, lb/in^3	0.07	0.07	0.164
Ultimate tensile stress, psi	1,000,000	500,000	180,000
Modulus of elasticity, psi	35,000,000	26,000,000	16,000,000

There are two other possibilities of improvement derivable from "whiskers": One is that their softening temperatures are far higher than for the polycrystalline form shown in Fig. 2, possibly not too far away from their melting point. The other possibility is that if it could be possible to control crystal axis orientation as the whisker is grown, then a material with considerably larger modulus and strength than shown in Table 4 might result.

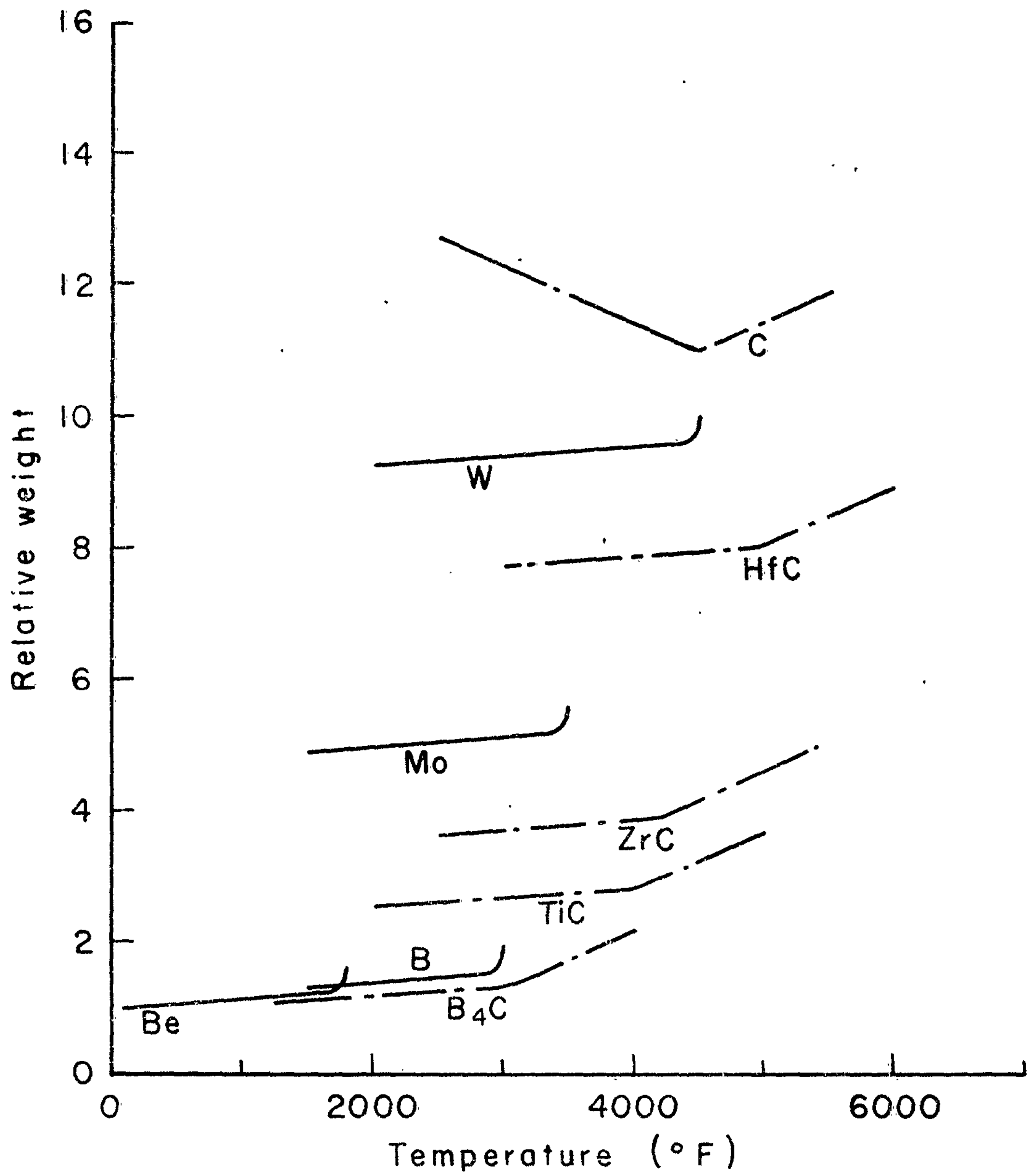

Fig. 6—The hypothetical relative weight of optimum whiskers

Comparison of tension components: whiskers vs conventional materials. In comparing weights of typical structural components made from various materials, basic material properties such as from Table 4 should be combined with any other feature peculiar to any one material. For whisker materials, we believe that a distinguishing feature will be the problem of fastening these hyper-strong sheets and rods to the adjacent structural components. These particularly intricate doublers and fasteners penalize whisker materials to a great extent: whereas at first one would have ventured to predict (from Table 4) that whisker materials seem to be showing a ten- to twenty-fold improvement over the present state-of-art, now — with the fastener penalty — weight reductions by a factor of only 4 to 10 seem possible. Considering a variety of applications for whisker materials, as listed in Table 5, it may be concluded that, in general, tensional structural weight could be cut down by a factor of 5 with whisker materials.

Table 5

WEIGHT REDUCTIONS IN TENSION STRUCTURES AFFORDED BY WHISKER MATERIALS

Component	Ratio of $\frac{\text{structural weight-conventional}}{\text{structural weight-whisker}}$
Cables and rods	10 to 23
Removable plates and sheets	about 4
Pressure vessels, tanks	up to 8
Miscellaneous:	
Porous sheet transpiration cooling	10
Prestressing cables for ceramics, carbon	8
Replacement for woven cloth	4
Rocket motor cases, exhaust cones	5
Tubing, ducts, cabin walls	8
Centrifugally tensioned components	4

This conclusion — that large order weight reductions are still possible in the future — should be very encouraging to astronautical investigators.

Buckling Components

Although structural components designed by buckling criteria will comprise a minor portion of a space vehicle, much is to be gained even in this field (and even in tension structures) when considering beryllium as a structural material. For three years now, we have monitored the history of this unusual metal, and this section will summarize some of our findings (Ref. 6)

Why beryllium? In comparing the weight of structures made up of thin-walled components, designed by elastic buckling criteria, a good first approximation to their relative weight, when made of various metallic elements, can result from considering the ratio

$$\frac{\text{Density of element}}{\text{Density of aluminum}} \times \sqrt{\frac{\text{Modulus of aluminum}}{\text{Modulus of element}}}$$

Aluminum is here the basis of comparison of the metals, an aluminum compression structure being considered as weighing unity at 70°F. The data from Table 3 can then be used, resulting in the comparison of metallic elements shown in Fig. 7. It is significant that there is a tendency for the lower-numbered elements to result in lighter structures, and of these beryllium gives the lightest structure of all.

The properties of beryllium. The table below summarizes the mechanical properties of beryllium.

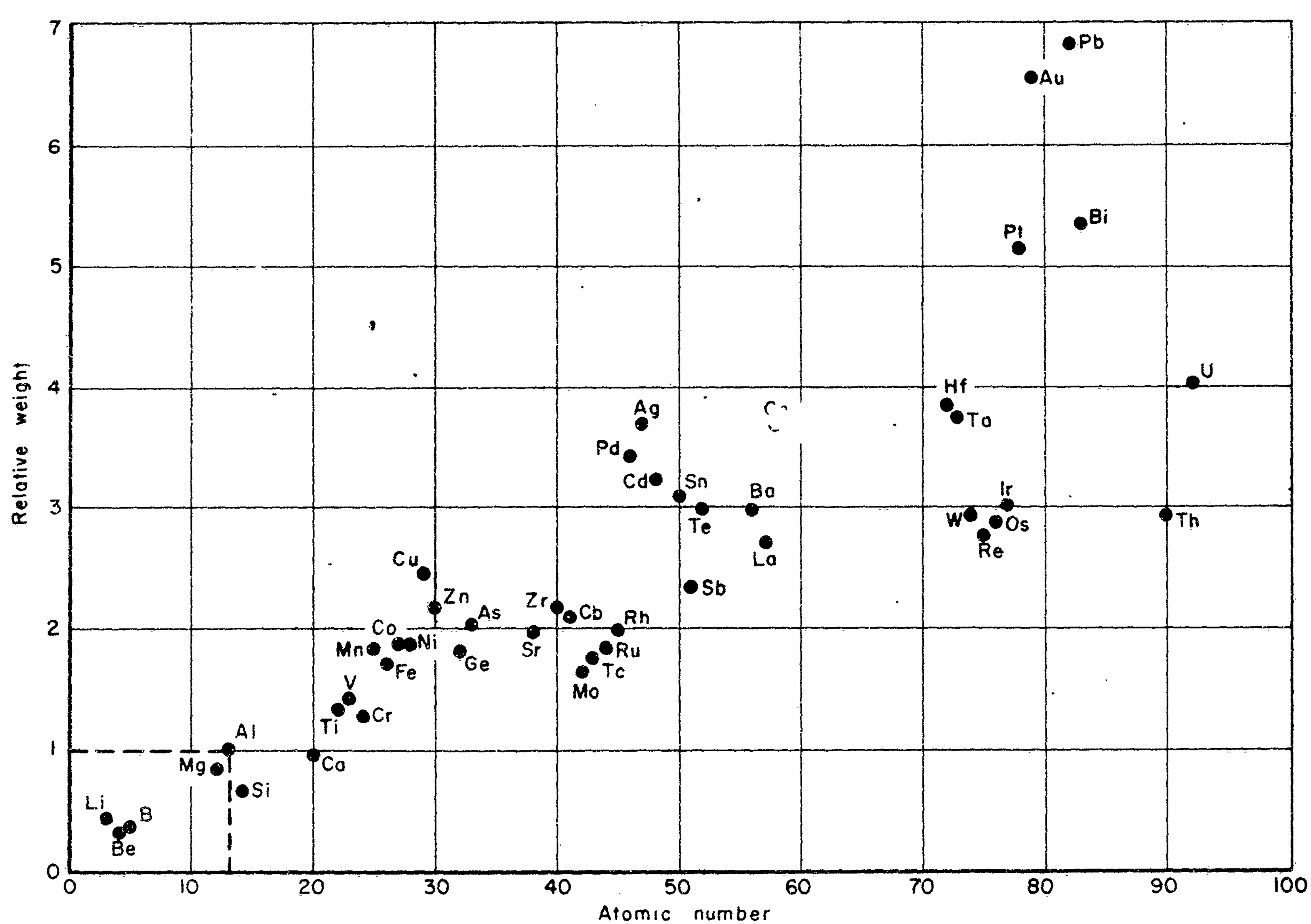

Fig. 7 —— Relative weights of thin-walled structures made of various metals; room temperature

Table 6

PROPERTIES OF BERYLLIUM

Density			0.066 lb/in.^{3}		
Modulus of elasticity,	70°F		44×10^6 psi		
	600°F		43×10^6 psi		
Tensile yield strength	70°F	best lab product:	95,000	mill product:	50,000 psi
	600°F		65,000		40,000 psi
Tensile ultimate strength	70°F		120,000		60,000 psi
	600°F		80,000		50,000 psi
Elongation under uniaxial stress	70°F		1% - 5%		
	400°F		8% - 16%		
	800°F		16% - 34%		
	1200°F		10% - 14%		

A combination of high thermal conductivity and specific heat makes beryllium very attractive in transient heating conditions. Corrosion, oxidation and erosion resistance are good up to 1200 - 1400°F.

At present beryllium ingot costs about $40 per pound, while sheets may run three to five times higher. Beryllium and its compounds are highly poisonous in the powder form, though much less dangerous when in solid shapes.

Comparison of beryllium and conventional materials. An accurate comparison of materials when used in thin-walled structures in compression, utilizing the complete stress-strain diagram of metals at various temperatures, is shown in Fig. 8, and shows the relative merit of beryllium and some conventional metals when used as compression sandwich panels. Beryllium affords a reduction in weight from 20 to 50 per cent up to temperatures of 1000°F.

When considering tension components, beryllium still looks very attractive: weight reductions, between 25 and 50 per cent are possible over

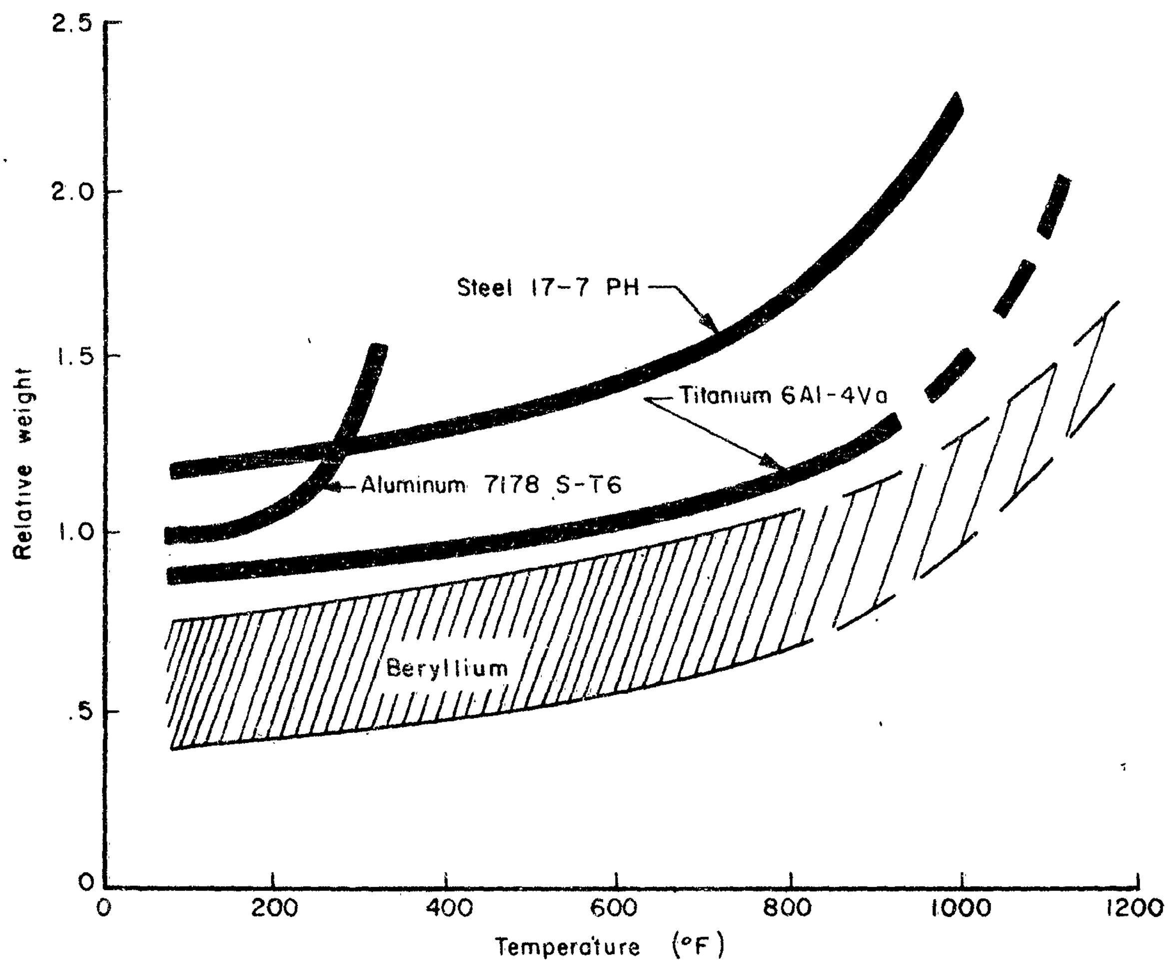

Fig. 8 — Relative weight of structural components of various materials at various temperatures

a wide temperature range, and the curves of Fig. 8 can again be used as a first approximation.

It should be cautioned that, just as with carbon and with ceramics, the ductility is a major problem yet to be alleviated in beryllium. As with all these other brittle materials, many of their potential advantages cannot be exploited, unless a clear solution can be had on the ductility problem.

Components Not Designed By Loads

Little can be generalized about the small fraction of the structure of a space vehicle that will be designed primarily by other criteria besides loads to be transmitted. In each instance and for each specific requirement, there are materials today that can function passably well. And in all these instances, some investigation can demonstrate that sizable improvements could be made in the future.

As an example, let us say that our design criterion in an artificial asteroid is the maximization of its visibility and observability from earth. Today's methods of producing large-area light-weight plastic films can result in respectably visible asteroids. We believe that the visibility could be quadrupled with a few month's development of unusually thin films and exotic shapes.

Similar statements can be made about possibilities of greatly enhanced materials for specialized applications such as transparency requirements, erosion and corrosion coatings, heat-transfer media, etc.

DISCUSSION: IMPROVEMENTS POSSIBLE WITH ADVANCED MATERIALS

Having quickly surveyed a few of the future possibilities in materials, it might be worthwhile to evaluate each of these possibilities in the light

of what performance improvements they afford. The list is by necessity condensed from excerpts from a variety of studies, and substantiation of the figures might be sketchy. Still, some indication as to the worth and value of these future materials is needed.

Tungsten and W^{184}. A temperature increment of 500°F to 1000°F (over molybdenum) appears possible with tungsten-built nuclear rocket motors. This alone can result in an increase in impulse of 10 to 20 per cent.

Carbon. If carbon structural shapes could be made to take tension, either by fibering, prestressing or any other technique, operating temperatures could be raised further in the heat exchanger of nuclear rocket engines. An increment of 500° to 1500°F (over W^{184}) represents another potential impulse increase over tungsten.

Carbides. If somehow a carbide could be developed from which to build critical components in an engine that operates at 5000 to 6000°F, this achievement might raise the impulse an additional small percentage over that of a carbon-built one.

Whiskers. If one can hypothesize the availability of whisker materials that can reduce the weight of tension structures weight to $\frac{1}{5}$ of their usual weight, then it has been estimated that the payload in a particular type of space vehicle might be doubled, all other parameters being left unchanged.

Beryllium. If metallurgical research could produce beryllium alloys with sufficient ductility, it appears that structural weight might be reduced by 20 to 50 per cent below today's capability. In space vehicles a definite increase in possible payload would be the result of the usage of hypothetically ductile beryllium.

Finally it should be emphasized that much research is needed on all these metals and compounds if their structural potentials are to be realized.

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